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The Non-Additivity of Heterochromatic Brightnesses

By A. DRESLER, Dr.Ing. (*Member*).

Summary

Although standard practice in up-to-date photometric laboratories shows that the expert is well acquainted with the intricacies of visual heterochromatic photometry, several recent publications on the non-additivity of heterochromatic brightnesses seem to indicate that the basic problems involved are not always fully understood by non-specialist photometrists. In this paper the author reviews the results of three independent investigations which all show that there is a definite, although non-linear relationship between the apparent brightness of surfaces of different colour and the photometric assessment of their brightness in terms of luminance as defined by the C.I.E. The general trend of this non-linear relationship between brightness and luminance is revealed and discussed. Finally, some suggestions are made how heterochromatic brightnesses can best be assessed visually in terms of their luminances.

(1) Introduction

Recent papers by R. H. Sinden(1), David L. MacAdam(2), L. M. Hurvich and D. Jameson(3), and by M. Tessier and F. Blottiau(4) indicate that some of the authors are not wholly familiar with the practical difficulties that inevitably occur when the brightnesses of two adjacent surfaces of different colour have to be matched by eye, and the result then used to express certain luminous properties of the two surfaces (or of the two light sources from which they receive their light) in terms of luminance* or any other of the photometric quantities.

This is somewhat remarkable, for not only do the leading photometric laboratories know very well what is entailed when coloured lights have to be assessed photometrically, but we also have in H. Koenig's excellent monograph(5) on the concept of brightness a very detailed account of all the physiological and technical problems involved. In two earlier articles(6), (7), the author made a first attempt to assess the various factors influencing the relationship between the brightnesses and luminances of heterochromatic lights.

The problem is important to anyone facing the problem of heterochromatic photometry, and a critical survey (in which the more recent American and French measurements are compared with earlier results) may, therefore, be justified.

(2) The Definition of Luminance and the Linear System of Photometry

Luminance (or Photometric Brightness) was defined by the International Commission on Illumination (C.I.E.) in 1939 by the following equation :—

$$B = K_m \int E_\lambda V_\lambda \, d\lambda$$

where : B = luminance in stilb,

K_m = maximum luminous efficiency of a monochromatic radiation in lm./w.,

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* Throughout this paper "brightness" stands for "apparent brightness," i.e., a psychological concept indicating how bright a surface appears to be, whereas "luminance" is used for "photometric brightness," i.e., a psycho-physical concept indicating how bright a surface is, expressed, for instance, in foot-lamberts.

$E_\lambda d\lambda$ = radiant intensity per unit area of radiant surface between the wavelengths λ and $\lambda + d\lambda$ in $W/cm.^2 \times ster.$

and V_λ = spectral photopic sensitivity of the standard observer as adopted provisionally by the C.I.E. in 1924 and confirmed in 1939.

Since luminance can be considered as the basic photometric concept from which all other concepts (e.g. luminous intensity, luminous flux, illumination) and their corresponding units (e.g. candela, lumen, lm./ft.^{2}) can be derived, it follows that the equation quoted above is the mathematical expression of the fact that we are using a linear system of photometry. Another way of saying the same thing is to state that in the adopted system of photometry, luminances may be added together regardless of their spectral composition. In addition, it implies that the function $V_\lambda = f(\lambda)$ to be used should be obtained by a method the results of which do not conflict with this linear system.

It should, however, be stressed that, contrary to the opinion expressed by Tessier and Blottiau[4], this definition of luminance and the corresponding linear photometric system do *not* postulate that the human eye should under all circumstances be capable of measuring luminances by assessing brightnesses. Just the reverse is true, for it is expressly stated in the relevant C.I.E. recommendation of 1939 that the results of photometric measurements must always comply with the definition of luminance quoted above. In other words, it is the task of the photometrist to ensure that the results he gets fit into the adopted linear system, just as he has to see that his results are identical with those the standard observer would have obtained, i.e., that they are consistent with the C.I.E. V_λ-function.

Most of the necessary precautions are quite obvious and nearly always taken into account. They are :—

(i) Provision of a suitable state of adaptation, i.e., field brightness;

(ii) Provision of a photometric field of suitable size;
(Both these conditions have to be chosen so that they are close to those used in assembling the data for the C.I.E. V_λ-curve.)

(iii) Neutral pre-adaptation of the observer's eye to avoid the effects of successive contrast;

(iv) The exclusion of dichromats and anomalous trichromats;

(v) A sufficient number of normal trichromats to average out second order deviations of individual spectral sensitivity curves from the C.I.E. standard V_λ-curve.

Koenig and others have stressed that one further very important precaution is necessary and has to be observed most painstakingly, namely, the avoidance of even the slightest simultaneous colour contrast within the photometric field. Statements made in papers[1], [3] and [4], however, suggest that very often, even in the presence of considerable colour differences between the two halves of the photometric field, the eye is considered capable of matching equal luminances while in fact it is matching equal brightnesses.

(3) The Equality-of-Brightness Match

The origin of this longstanding belief can be traced to H. E. Ives's classic paper [8] in which he states that provided certain precautions are observed in regard to size and luminance of the photometric field, it is possible to arrive at one and the same spectral sensitivity curve for any one observer regardless of whether an equality-of-brightness match or the flicker method is used. This statement, although substantially correct,

has proved to be extremely misleading, because it has caused many to believe that methods which produce the same spectral sensitivity curve *must* always give identical photometric results provided the same general conditions of observation are maintained. That such a conclusion is fallacious can be shown by going back to some of Ives's original figures, as first pointed out by M. Luckiesh[9], [10]. In fact, if Ives's photometric readings, obtained at various wavelengths by the two methods, are compared with each other directly in terms of luminous intensity (or luminance), instead of being first converted into relative spectral sensitivity figures, the basic differences immediately appear. Table 1 contains a few of Ives's figures taken from page 183 of his paper. They refer to a field size of 1.86 deg. and to the two medium values of field luminance used (8.9 and 68 relative units). All measurements were taken against a standard comparison lamp run at a colour temperature of 2,070 deg. K and having

Table 1.

Some of the Spectral Photometric Measurements Reported by H. E. Ives.

Wavelength of spectral light mμ	Field luminance : 8.9 rel. units			Field luminance : 68 rel. units		
	Equality of brightness	Flicker	Equ. of Br. / Flicker	Equality of brightness	Flicker	Equ. of Br. / Flicker
652.5	25.3	23.0	1.10	—	—	—
642	43.8	37.9	1.16	34.4	30.4	1.13
632	59.1	53.4	1.11	50.5	45.5	1.11
622	80.1	68.6	1.17	65.3	59.6	1.09
612	95.3	82.4	1.16	78.6	73.4	1.07
593	116.7	102.8	1.14	99.6	93.9	1.06
574	115.2	106.4	1.08	100.5	101.6	0.99
555	101.1	93.4	1.09	91.2	88.3	1.03
545	91.2	79.3	1.15	81.7	79.4	1.03
535	78.9	67.0	1.18	69.2	66.6	1.04
526	59.9	50.5	1.19	52.7	50.9	1.04
517	40.1	31.6	1.27	32.0	31.5	1.02
508	22.5	19.3	1.17	—	—	—

a dominant wavelength of 588 mμ. The observer was required to compare the luminances produced by the various wavelengths with that produced by the comparison source, either directly in an equality-of-brightness match or with the help of a flicker photometer. The results (in relative figures) are quoted in the second and third columns of Table 1 for the lower of the two field luminances and in the fifth and sixth columns for the higher one. In the fourth and the last columns the corresponding ratios of equality-of-brightness and flicker results are given.

In Fig. 1 these ratios have been plotted against the wavelength of the spectral light measured. Although the points scatter somewhat because of the inaccuracy inherent in an equality-of-brightness match of two lights of widely different colour, the two curves drawn through them show two common and significant features :—

(i) The relative luminous intensities obtained by the equality-of-brightness match are always (with one exception) higher than those resulting from flicker measurements.

(ii) The differences in the results of the two methods tend to become smallest when the hue of the spectral light to be measured approaches that of the comparison lamp.

The important fact, however, which emerges from these figures and curves is

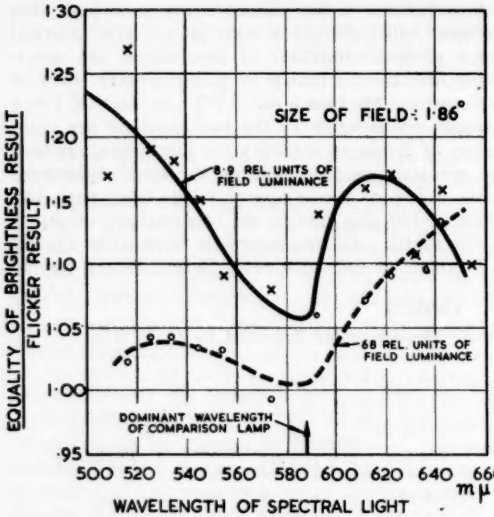

Fig. 1. Relation between Equality-of-Brightness and Flicker measurements of spectral lights. (After H. E. Ives.)

that heterochromatic photometry in an equality-of-brightness match is subject to non-linear distortions, provided one can say that the results obtained with the flicker method are substantially linear, i.e., additive.

(4) The Flicker Method

That heterochromatic measurements taken with a flicker photometer follow the law of additivity was first stated by A. Kohlrausch[11]. More recent measurements by the author[6], though confined to a limited range of luminances, seemed to confirm Kohlrausch's result, but when the luminance range was extended beyond a ratio of 1 : 3 it was found independently by M. Jaggi[12] and the author[13] that slight deviations from linearity, particularly in the red, do occur. The situation can be best described by referring to H. Koenig's summary[14], which states :—

(i) When highly saturated colours are measured with a flicker photometer the results will deviate by only 1-2 per cent. from linearity, provided the luminance range is kept within a ratio of 1 : 2.

(ii) Flicker measurements of highly saturated colours depend to the same extent (i.e., to 1-2 per cent.) on the colour of the comparison lamp.

(iii) When field luminance is increased from 1 to approximately 600 ft.-L., measurements in the red part of the spectrum will give results that are lower by as much as 30 per cent.

(iv.) Flicker measurements are also influenced by slight seasonal variations in an observer's spectral sensitivity. In extreme cases these variations can account for a variation in results of ± 5 per cent. with time of year.

In addition, it should be mentioned that the deviation from linearity which, as stated above in paragraph (iii), is negative with increasing luminance in the red, turns out to be positive but less pronounced in the blue. It will, however, be obvious from what has been said that in flicker photometry the deviations from additivity can be expected to be small compared with those obtained in an equality-of-brightness match. That this is, in fact, true can be proved by listing in Tables 2 and 3 a few of the results the author published in 1937[6]. Table 2 refers to the flicker method and Table 3 to the equality-of-brightness match. The figures given represent the average results

obtained from nine observers, who were required to compare various coloured lights against a normal tungsten vacuum lamp. The coloured lights are classified by their dominant wavelength λ_d and their saturation σ (Excitation purity, based on x = 0.333 and y = 0.333 as "white"). Both a fairly large photometric field (7 deg.) and a rather unusually small one (1 deg. 10 min.) were used in these measurements.

The figures of Tables 2 and 3 show that the flicker results obey the additivity law within the limits quoted above, whereas the equality-of-brightness match displays a non-linear relationship between brightness and luminance.

Table 2.

The Additivity of Flicker Measurements Within a Limited Range of Field Luminance.

Colour of light			Relative luminous intensity and deviation from additivity	
Name	λ_d	σ	Field : 7 deg.	Field 1 deg. 10 min.
	mμ	per cent.	per cent.	per cent.
Red	620	100	32.2	31.8
Blue	504	22	67.8	68.2
Red and Blue	605	59	99.6 : −0.4	98.1 : −1.9
Red	620	100	38.4	38.5
Green	560	83	61.6	61.5
Red and Green	590	93	99.7 : −0.3	101.3 : +1.3
Red	620	100	23.2	23.0
Yellow	585	100	76.8	77.0
Red and Yellow	589	100	100.5 : +0.5	100.2 : +0.2
Green	560	83	32.4	32.4
Yellow	585	100	67.6	67.6
Green and Yellow	577	93	98.8 : −1.2	99.1 : −0.9
Green	560	83	43.1	43.0
Blue	504	22	56.9	57.0
Green and Blue	545	35	100.8 : +0.8	99.7 : −0.3
Yellow	585	100	67.0	67.6
Blue	504	22	33.0	32.4
Yellow and Blue	578	61	100.9 : +0.9	101.0 : +1.0

Luminance of field : ≧ 1.0 ft.-L.
Colour of comparison lamp: λ_d = 585 mμ σ = 67 per cent.

(5) Brightness Versus Luminance in an Equality-of-Brightness Match

In order to assess the nature of this non-linearity and the factors controlling it, the measurements forming the basis for Tables 2 and 3 were used to compute the ratios of corresponding values of luminous intensity obtained by the two methods. They were then assembled in a diagram (Fig. 2), which is similar to that of Fig. 1. Fig. 2 refers to measurements with the 7 deg. field only. Since we know that these particular flicker measurements are additive, i.e., represent true luminance figures (or their equivalent), the ratios given in the ordinate of Fig. 2 in turn represent a

Table 3.
The Non-Additivity of Equality-of-Brightness Measurements.

Colour of light			Relative luminous intensity and deviation from additivity	
Name	λ_d	σ	Field : 7 deg.	Field : 1 deg. 10 min.
	mμ	per cent.	per cent.	per cent.
Red	620	100	40.7	42.6
Blue	504	22	59.3	57.4
Red and Blue	605	59	70.5 : −29.5	61.3 : −38.7
Red	620	100	47.2	44.7
Green	560	83	52.8	55.3
Red and Green	590	93	59.7 : −40.3	59.5 : −40.5
Red	620	100	33.9	35.1
Yellow	585	100	66.1	64.9
Red and Yellow	589	100	88.3 : −11.7	85.0 : −15.0
Green	560	83	42.4	43.7
Yellow	585	100	57.6	56.3
Green and Yellow	577	93	77.7 : −22.3	74.2 : −25.8
Green	560	83	46.3	47.5
Blue	504	22	53.7	52.5
Green and Blue	545	35	81.5 : −18.5	72.4 : −27.6
Yellow	585	100	61.2	63.0
Blue	504	22	38.8	37.0
Yellow and Blue	578	61	81.5 : −18.5	84.5 : −15.5

Luminance of field: $\geq$ 1.0 ft.-L.
Colour of comparison lamp: λ_d = 585 mμ, σ = 67 per cent.

brightness/luminance (B/L) ratio, indicating how much brighter the various coloured lights used appear to be—when measured directly against a normal tungsten lamp—than would follow from their luminances.

This, however, means that by using both the equality-of-brightness match and the flicker method in a particular heterochromatic comparison we have found a way of *measuring* brightness as well as luminance, but it should be borne in mind that luminance indicates a well-defined luminous property of a surface and is by definition completely independent of the colour of the comparison source employed, whilst the brightness figure does depend on the colour of the other half of the photometric field and therefore has a rather restricted meaning.

When comparing the curves in Fig. 2 with those in Fig. 1, it should be realised that the latter refer to *one* observer and two fixed luminances, whereas the former represent the average of nine observers (whose Y/B ratios were all within the limits of 0.94 to 1.05) and refer to luminances varying by a factor of about 3.

Before discussing these results any further it seems advisable to check how the more recent measurements on the non-additivity of brightnesses published by MacAdam[2], and by Tessier and Blottiau[3] fit into the scheme so far developed.

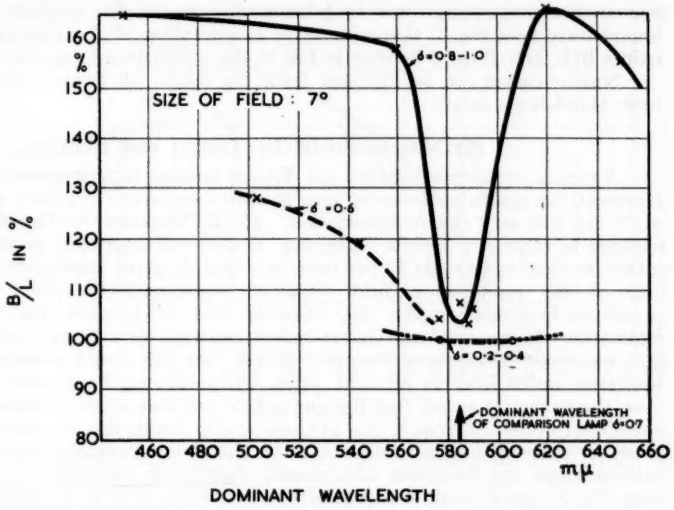

Fig. 2. Brightness / Luminance ratio (B/L) in an Equality-of-Brightness match. (Average of nine observers.)

MacAdam's, as well as the French, measurements include some colours in the purple range, so that they embrace the whole colour circle. Since the dominant wavelength of purples is usually given in terms of the corresponding complementary wavelength but with a minus sign affixed, we cannot use a diagram on the lines of Figs. 1 and 2 to include the purples. To do this, dominant wavelength has to be replaced by another classification of hue, the steps of which will arrange themselves in a complete circle. A suitable method was suggested by M. Richter[15]. It is directly related to the C.I.E. Colour-Classification System and uses the hue number $n = R - 5\eta$, where R is either 6, 16 or 26 depending on whether x, y or z is the smallest of the three chromaticity co-ordinates. η is given by

$$\frac{x - y}{1 - 3z} \quad \text{or} \quad \frac{y - z}{1 - 3x} \quad \text{or} \quad \frac{z - x}{1 - 3y}$$

respectively. According to this system of hue numbers, a dominant wavelength of 620 mμ corresponds to an n of about 4, 550 mμ corresponds to n = 8, 530 mμ to n = 10, 500 mμ to n = 16 and 465 mμ to n = 22. The purples start at about n = 23 near the violet end of the spectrum and extend over 30 (highest figure for n) to n = 3 at the red end, thus completing the circle.

If these hue numbers n are used to replace the values of dominant wavelength λ_d given in Fig. 2, and arranged together with the corresponding figures for excitation purity σ and brightness/luminance ratio B/L in a polar-diagram, we arrive at two curves—one for $\sigma = f(n)$, the other for $B/L = f(n)$, as shown in Fig. 3. The radii of this polar-diagram correspond to the 30 possible hue numbers n, whereas the concentric circles refer to both σ and B/L, σ being 1.0 for the largest circle which therefore replaces the spectral locus and the purple line of the standard C.I.E. colour chart. σ decreases in steps of 0.1 down to zero at the centre point, which in turn represents x = 0.333 and y = 0.333. B/L, on the other hand, is taken as 1.0 at the centre and increases in steps of 0.1 up to 2.0 along the outermost circle.

When the relative position of the $\sigma = f(n)$ curve is compared with that of the $B/L = f(n)$ curve, the low values of B/L in the yellow range (n = 5 to n = 7) are very apparent; as shown later, this can only partly be attributed to the fact that the

hue number of the comparison lamp lies in this range. The diagram also shows, more impressively than Fig. 2, that a decrease in saturation of the coloured light tends to reduce B/L, even if the difference in hue to the comparison lamp remains considerable.

Similar curves can be obtained from the results of Tessier and Blottiau[4] and from MacAdam's data[2].

(6) Measurements by Tessier and Blottiau

A typical curve published by the French authors is reproduced in Fig. 4, which represents the results obtained by one of their observers (T) with a photometric field of 15 deg. and an "ocular illumination" of 216 Trolands.* The observer was first required to make a red-white (3,500 deg. K colour temperature) equality-of-brightness match; he then had to add 10 per cent. of a certain green luminance, while the white half of the photometric field remained unchanged. In order to restore the equality-of-brightness match the observer had to readjust the amount of red luminance. If the first and second match belonged to a linear system of judgment then the result should have been that 90 per cent. red would produce an equality-of-brightness match after 10 per cent. green luminance had been added. Fig. 4, however, shows that in actual fact the amount of red had to be *increased* to regain the equality-of-brightness match, the obvious reason being that by adding 10 per cent. green the resultant hue had shifted towards the yellow (and towards that of the comparison lamp), and the colour had become slightly less saturated. This, as is known from Fig. 3, should result in a considerable reduction of B/L; in other words, the red contribution to the green-red mixture now appears far less bright than before, and its luminance has to be increased, instead of being decreased, to restore the equality-of-brightness match. The same effect applies to the other end of the curve where

* An "illumination" of 1 Troland corresponds to the amount of light entering a pupil of 1 mm² opening when the eye is looking at a luminance of 1 cd/m².

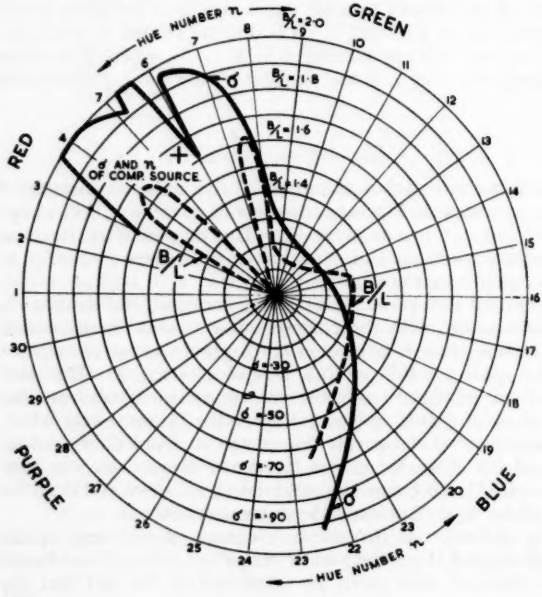

Fig. 3. Measurements shown in Fig. 2 expressed in terms of $\sigma = f(n)$ and $B/L = f(n)$.

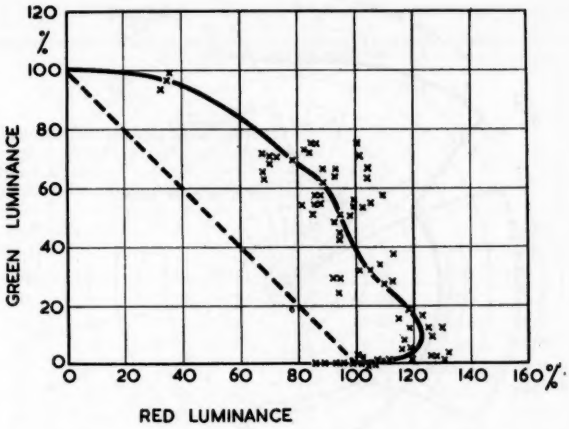

Fig. 4. Red and green luminances required to maintain constant brightness for various mixtures of red and green. (After Tessier and Blottiau.)

adding 10 per cent. red still requires 100 per cent. green instead of 90 per cent. to restore the equality-of-brightness match.

The main difficulty in interpreting the curve of Fig. 4 in terms of B/L is governed by the fact that we do not know the figures for B/L for the two extreme values, namely 100 per cent. red and 100 per cent. green. This difficulty, however, can be overcome by making the following two reasonable assumptions :—

(i) That B/L cannot be less than 1.0 (any mixture of the red and green lights used by the French authors has an excitation purity of 87 per cent. or more, whereas the comparison source has a σ of 39 per cent.;

Table 4.

French Additivity Measurements: Red plus Green. Observer T. Large Field.

Adding Green to Red			Adding Red to Green			Average				
Added green luminance	Required red luminance	(B/L) Red	Added red luminance	Required green luminance	(B/L) Green	Percentage Luminance		B/L	n	σ
						Red	Green			
Per cent.	Per cent.		Per cent.	Per cent.						Per cent.
0	100	1.65	0	100	2.19	100	0	1.65	4.48	100
10	122	1.22	10	100	1.97	90	10	1.13	4.93	98
20	118	1.12	20	99	1.77	80	20	1.02	5.43	95.4
30	106	1.09	30	97	1.58	70	30	1.02	5.85	93.6
40	100	1.00	40	95	1.39	60	40	1.02	6.34	91.7
50	96	0.86	50	90	1.22	50	50	1.04	6.86	90.3
60	90	0.73	60	83	1.05	40	60	1.13	7.40	88.7
70	78	0.64	70	77	0.85	30	70	1.30	7.96	87.2
80	67	0.49	80	68	0.64	20	80	1.51	8.58	86.9
90	50	0.33	90	60	0.37	10	90	1.80	9.22	88.2
100	0	—	100	0	—	0	100	2.19	9.80	91.2

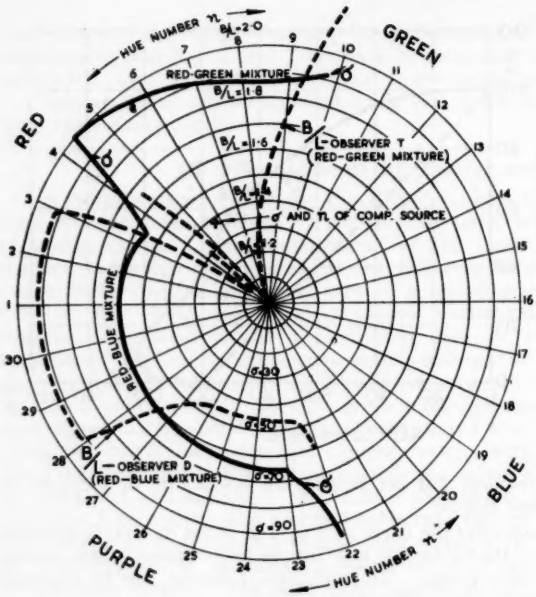

Fig. 5. French additivity measurements expressed in terms of $\sigma = f(n)$ and $B/L = f(n)$.

(ii) That B/L should be very close to 1.0, where the hue of the red-green mixture turns yellow and is similar or even equal to that of the comparison lamp.

With these two assumptions it is a simple matter of trial and error to arrive at probable B/L figures for 100 per cent. red and 100 per cent. green and to calculate the intermediate figures. If values of B/L = 1.65 for 100 per cent. red, and B/L = 2.19 for 100 per cent. green are adopted, the intermediate figures compared by starting first from 100 per cent. red and then from 100 per cent. green, and the corresponding two B/L figures averaged according to their percentage luminance values, the figures listed in Table 4 and the polar-diagram of Fig. 5 are obtained. Fig. 5 also includes a second series of measurements by another observer (D) for a mixture of red and blue under otherwise almost identical conditions of observation (Field size = 15 deg., "ocular illumination" = 180 Trolands). For detailed figures of this second series see Table 5.

Because of the assumptions on which these B/L curves were developed, they do not necessarily represent the "true" B/L figures for the two observers concerned, but they should indicate the trend of B/L as a function of n and σ. If the curves of Fig. 3 and Fig. 5 are compared where they cover the same range of n (Red to Green-Yellow), a similar drop in the value of B/L towards 1.0 is apparent. It is also clear that the degree of saturation of the coloured lights (outside the yellow range) greatly influences the value of B/L. The second French observer (D) has a lower B/L in the red than his colleague and his B/L for a highly saturated blue does not exceed 1.60. The reddish purples, however, appear to him particularly bright, and this in spite of his first following the normal trend of having a lower B/L when saturation decreases in the red between n = 4.5 and n = 3.5.

(7) Measurements by D. L. MacAdam

MacAdam was not concerned primarily with B/L ratios; he was trying to establish loci of constant hue and constant brightness in the C.I.E. colour chart by gradually

Table 5.

French Additivity Measurements: Red plus Blue. Observer D. Large Field.

Adding Blue to Red			Adding Red to Blue			Average				
Added blue luminance	Required red luminance	(B/L) Red	Added red luminance	Required blue luminance	(B/L) Blue	Percentage Luminance		B/L	n	σ
						Red	Blue			
Per cent.	Per cent.		Per cent.	Per cent.						Per cent.
0	100	1.30	0	100	1.60	100	0	1.30	4.48	100
10	108	1.08	10	93	1.55	90	10	1.05	4.06	74.8
20	95	1.09	20	84	1.52	80	20	1.35	3.51	55.9
30	53	1.72	30	72	1.55	70	30	1.92	2.92	58.0
35	53	1.59	40	61	1.57	65	35	1.92	29.61	59.2
40	53	1.47	50	60	1.60	60	40	1.90	28.02	60.0
50	50	1.30	60	25	2.55	50	50	1.45	25.92	62.2
60	41	1.27	65	22	2.54	40	60	1.45	24.56	64.0
70	31	1.26	70	20	2.39	30	70	1.47	22.97	66.3
80	23	1.13	80	20	1.60	20	80	1.44	22.92	68.5
90	14	0.93	90	20	.80	10	90	1.49	22.39	78.5
100	0	—	100	0	—	0	100	1.60	22.09	95.2

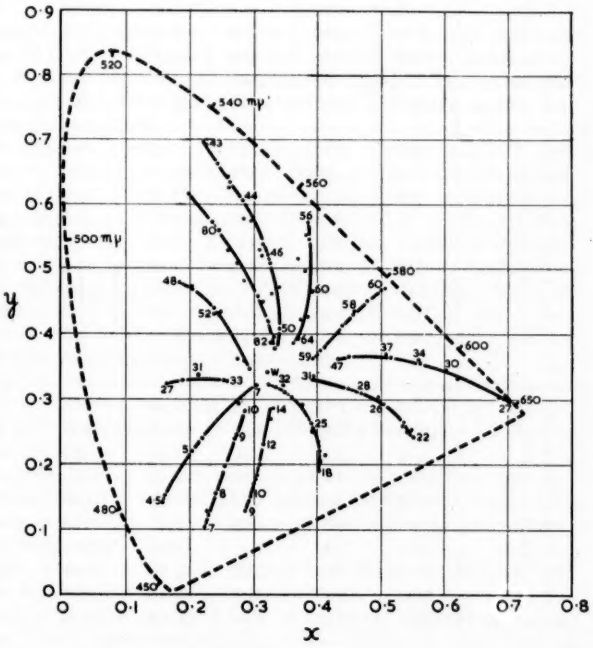

Fig. 6. Loci of constant hue with dark surround and 10 deg. field. Luminances (foot lamberts) necessary for constant brightness for each hue are shown by numbers printed near typical points. (After D. L. McAdam.)

decreasing the saturation of a variety of strong colours. In order to maintain a constant brightness throughout, MacAdam had to increase the luminance of his colours of constant hue and brightness when de-saturating them.

A typical set of his results is reproduced in Fig. 6, corresponding to Fig. 4 in MacAdam's paper(2), which shows the loci of constant hue for one observer with a dark surround and a 10-deg. field. The luminances (in foot-lamberts) which were necessary to maintain the impression of constant brightness for each hue are shown by the figures printed near typical points. Similar sets of curves were obtained for a

Table 6.

MacAdam's Measurements of Luminances for Constant Brightness (Field Size: 10 deg.)

Colour of surround	Trichromatic Co-ordinates of Saturated Colour			Hue Number n	Excitation purity σ	Luminance for n, σ	Luminance for white or grey	B/L
	x	y	z					
						ft.-L	ft.-L	
Dark Surround	.165	.140	.695	21.43	.765	4.5	7	1.55
	.170	.320	.510	17.94	.568	27	33	1.22
	.180	.480	.340	14.48	.466	48	>52	>1.08
	.200	.620	.180	10.57	.582	<80	82	>1.03
	.220	.690	.090	9.22	.800	43	50	1.16
	.390	.580	.030	7.05	.920	56	64	1.14
	.510	.475	.015	5.72	.950	60	59	.98
	.700	.300	—	4.00	1.000	27	47	1.74
	.540	.250	.210	2.08	.704	22	31	1.41
	.400	.180	.420	26.72	.725	18	32	1.78
	.290	.130	.580	23.62	.782	9	14	1.56
	.220	.105	.675	22.65	.700	7	10	1.43
Tungsten Light Surround (n=5.64, σ=.570) of 10 ft.-L.	.145	.080	.775	21.85	.910	2.7	6	2.22
	.170	.280	.550	18.75	.600	15	21	1.40
	.195	.495	.310	13.77	.430	48	55	1.14
	.220	.730	.050	9.0	.910	47	>50	>1.06
	.380	.580	.040	7.14	.880	52	60	1.15
	.510	.470	.020	5.79	.935	56	57	1.02
	.710	.290	—	3.90	1.000	20	>24	>1.20
	.550	.240	.210	1.80	.760	24	34	1.42
	.385	.170	.445	25.39	.737	9	>13	>1.44
	.240	.115	.645	22.90	.686	5	8	1.60
Near White Surround (n=22.84, σ=.195) of 9 ft.-L.	.150	.075	.775	21.96	.905	3.7	>8	>2.16
	.170	.270	.560	18.85	.665	14	18	1.29
	.190	.470	.340	14.86	.433	47	>57	>1.21
	.215	.710	.075	9.20	.840	40	>50	>1.25
	.375	.580	.045	7.19	.870	<54	59	>1.09
	.500	.470	.030	5.97	.910	51	55	1.08
	.710	.290	—	3.90	1.000	22	>30	>1.36
	.550	.230	.220	2.76	.806	22	36	1.63
	.380	.165	.435	25.45	.745	9	>11	>1.22
	.240	.110	.650	22.94	.705	4.6	7	1.52

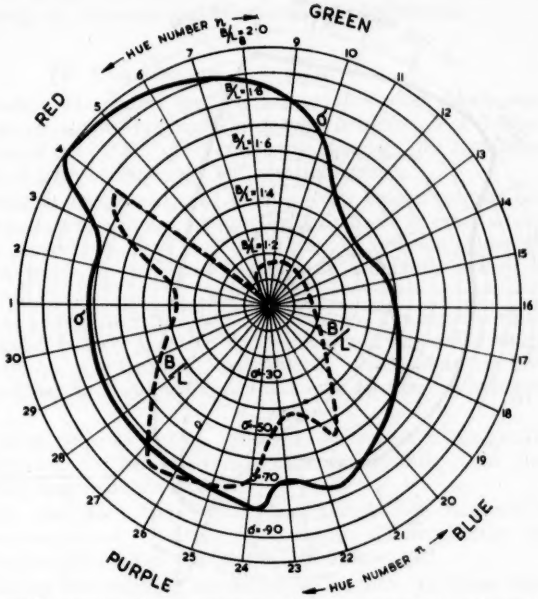

Fig. 7. B/L=f (n σ) for dark surround. (Based on McAdam's data.)

number of adaptation backgrounds ranging from tungsten white to saturated reds and blues produced by fluorescent cloths. By using the foot-lambert figures ascribed to the innermost and outermost points of every line of constant hue and brightness, the B/L ratios for the most saturated colours as compared with the B/L ratio of 1.00 for the central white or grey can be calculated.

If the trichromatic co-ordinates quoted by MacAdam are transformed into hue number n and excitation purity σ, results such as those given in Fig. 6 can be plotted on the polar-diagram used in Figs. 3 and 5. Out of the numerous measurements reported by MacAdam those three sets were selected which should be of the greatest interest to photometrists generally, viz., dark surround, tungsten light surround of 10 ft.-L luminance, and near-white surround (slightly bluish) of 9 ft.-L luminance. Table 6 gives the individual figures taken from MacAdam's charts, and Figs. 7, 8, and 9 show the corresponding polar-diagrams. It should be borne in mind that MacAdam arrived at his B/L ratios by a step-by-step method which did not require the eye to match the full colour difference to white or grey at any time.

Apart from the fact that the influence of the three surround brightnesses considered is of secondary importance, it will be noted that the general trend of the B/L curves given in Figs. 7, 8, and 9 is very much the same as that shown by the curves of Figs. 3 and 5, the outstanding points being :—

(i) B/L is always lowest in the yellow, however saturated the yellow may be. (This is independent of the fact that in normal photometric work B/L will tend to be low in this range because of the colour of the normal incandescent comparison lamp.)

(ii) Saturated reds, greens, blues and purples are likely to produce the highest values of B/L.

(iii) When the saturation of a coloured light is decreased without changing its luminance it will appear less bright.

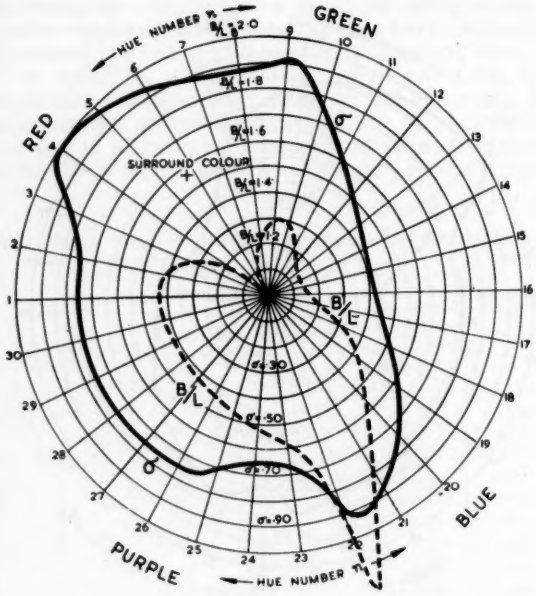

Fig. 8. B/L=f (n σ) for tungsten light surround of 10 ft.-L. (Based on McAdam's data.)

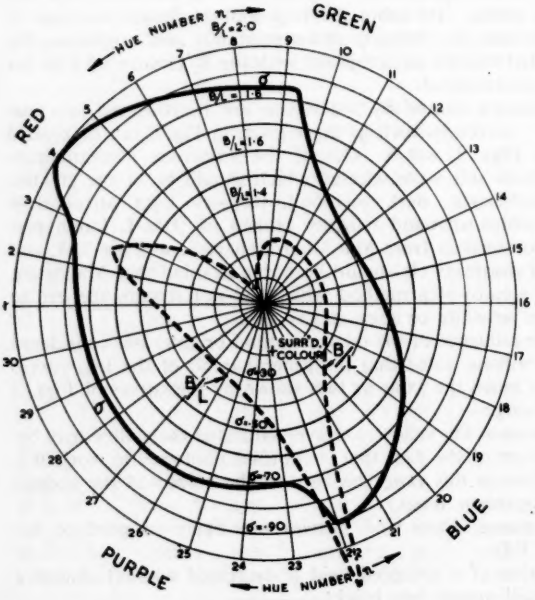

Fig. 9. B/L=f (n σ) for near white surround of 9 ft.-L. (Based on McAdam's data.)

(iv) There is a wide range in which B/L may vary for one and the same colour, depending on observer and conditions of observation.

(8) Conclusions

Tessier and Blottiau remark in their paper that the non-additivity they experienced in a series of heterochromatic equality-of-brightness matches "is obviously a flagrant contradiction to the hypothesis of the C.I.E." This is not true because "the hypothesis of the C.I.E." is not concerned with brightnesses, but with luminances.

Brightnesses when assessed in the presence of even a slight colour contrast are generally non-additive, whereas luminances are additive *by definition*; in other words, it is the responsibility of the observer to make sure that he is in a position to express his brightness assessments in terms of luminance, i.e., within the linear system of photometric concepts and units.

Earlier it was said that in addition to the specifically listed five precautions which have to be observed to achieve "linear" results, a sixth one would be needed which, although of particular importance, was frequently overlooked. From what has been discussed in this paper it should be clear why photometrists must insist on the following precaution :—

(vi) Arrangements should be made so that no noticeable differences in hue and/or saturation occur between the two halves of the photometric field (i.e., simultaneous contrast has to be avoided).

It should be stressed that the need for "no noticeable differences in hue and/or saturation" cannot be over-emphasised. Even a small colour difference like that between vacuum and gas-filled tungsten lamps creates a B/L of at least 1.02.

Practical means of ensuring this working condition (in addition to those listed earlier) are :—

(i) The use of a colour filter of known spectral (and total visual) transmission in front of the comparison lamp which will make the latter appear to have the colour of the light to be measured (i.e., the well-known filter method of visual heterochromatic photometry).

(ii) The use of the flicker photometer instead of the equality-of-brightness match for small colour differences, subject to all other precautionary measures discussed above.

(iii) The combination of (i) and (ii) where it is not possible to arrive at colour identity by method (i).

Method (iii) is of practical importance when measuring the luminance of isolated spectral lines (e.g., sodium lamps), where the "colour correction" filter in front of the comparison lamp should preferably not be selected to match the colour of the spectral line (e.g., an ordinary yellow filter that transmits the red as well), but to isolate a narrow spectral band extending to either side of the spectrum line to be measured. The slight colour difference which is then likely to remain can be easily handled by using a flicker photometer. The principal advantage of this method of "energy" filtering instead of "colour" filtering is that it suppresses the influence of the individual observer's spectral sensitivity which may differ appreciably from the C.I.E. V_λ-curve, even within the so-called normal range of colour vision.

There remains one problem to be discussed: the question how one should determine individual V_λ curves which, according to the C.I.E. definition of luminance, should denote the relative sensitivity of the eye to spectral luminances and not to spectral brightnesses. At first sight this may appear to be an argument which runs in a circle, for it has been said that luminance cannot be defined without knowledge

of V_λ. Now it is being asked how V_λ should be determined so that it fits into the linear system of photometry as defined by $B = K_m \int E_\lambda V_\lambda d\lambda$. This is due to the fact that V_λ cannot be measured without employing one of the available methods of visual heterochromatic photometry, and it is therefore only logical to ask that in obtaining V_λ a method should be used the results of which do not conflict with the basic requirement of linearity. From what has been said above it should be clear that there is only one method which is most likely to give "linear" results; this is the combination of the step-by-step method with the flicker photometer as a means of assessing the equality of brightness of the two halves of the photometric field, the colour difference of which should be kept to a practicable minimum.

Since the C.I.E. V_λ-curve is at present under review (at least for the short-wave range below 440mμ), and various research workers may be attempting to establish a truly reliable standard V_λ-curve, this brightness-versus-luminance problem is not only of practical importance in ordinary routine photometry, but also of considerable fundamental importance.

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Contributed Discussion

DR. J. W. T. WALSH: Dr. Dresler's excellent review of work on the additivity of brightness brings out very clearly the important fact that the relation between luminance and brightness (or luminosity) is dependent, even for a single eye, on a large number of factors which may or may not be under the control of the experimenter.

When the C.I.E. in 1924 adopted (provisionally, be it noted) a table of values of V_λ, it was known that there were sources of uncertainty, even when the average of a large number of individual observers was taken, but the number and range of these uncertainties were, mercifully, not realised or the adoption of the table might well have been delayed for a considerable time. It must be remembered that, at that period, physical photometry was still in its infancy and the adoption of values for V_λ was intended to help in ordinary visual heterochromatic photometry. I don't think the fact that it did, in reality, establish a physical photometric scale was really recognised at the time.

To-day the picture is entirely different. Photometric measurement is now a purely physical measurement arranged to give results which will accord, sufficiently for all practical purposes, with the results of visual observation under normal conditions. (This allows the measurements to be made visually under suitable conditions.) The

system therefore conforms with ordinary physical laws, including that of additivity, and it follows that departures from additivity such as those discussed by Dr. Dresler, are mainly of interest (a) to the worker in physiological optics and (b) to the worker in photometry under conditions which do not come within the description "normal," e.g., at low luminance levels.

I feel that this review may perform yet one more useful function by emphasising the necessarily somewhat arbitrary nature of the V_λ values. From time to time we are plagued with those who "discover" afresh that the values are "in error" at one part or other of the visible spectrum, and the extent of the "error" and its position in the spectrum depend on the conditions of observation used by the particular experimenter. Once it is generally recognised that V_λ is a convention and not an invariable property of the human eye, there should be no more attempts to tinker with it unless it can be proved beyond all doubt that, within any particular special range, it differs from the values found for the average human eye under normal conditions by an amount which is greater than can be tolerated in practical every-day photometric and colorimetric work.

PROF. W. D. WRIGHT (Imperial College of Science and Technology, London): Dr. Dresler's paper discusses a matter of great interest and importance at the present time, but I do not feel he has posed the essential dilemma very clearly. While his discussion of the proper conditions for visual heterochromatic photometry is not entirely irrelevant, it is not very pertinent (except in connection with the measurement of the V_λ curve) since most heterochromatic photometry is nowadays carried out by means of physical photometers, and the flicker photometer is very largely outdated in the industrial laboratory. Dr. Dresler does not mention physical photometry at all, but in fact the problem of measuring luminances and other photometric quantities on an additive scale presents no great difficulty by this means.

The real problem is this: When heterochromatic measurements have been made in accordance with the C.I.E. conventions in which additivity is correct by definition, are the results in sufficient conformity with our visual impressions to be of value to the lighting engineer? This question has still to be answered, but there is evidence that, under some conditions at least, the results are in conflict with what we see. Thus, it can happen that the light output F_1 from a fluorescent lamp A may be greater as measured photometrically than the output F_2 from lamp B, yet because of a difference in colour between the two lamps, B may appear subjectively the brighter of the two. This can evidently be of some concern to the lamp salesman, if he were thinking of charging more for lamp A than lamp B on account of its greater lumen output!

Unless, therefore, equality of luminance implies fairly close equality of subjective brightness, and unless differences of luminance are ranked in the same order as the corresponding differences of subjective brightness, heterochromatic photometry would seem to be of doubtful value. I have, in "Photometry and the Eye," dealt at greater length with this question and would only add here the further comment on Dr. Dresler's paper that since the sensation of brightness cannot be measured, the question of its additivity does not arise. There is a danger, however, of getting at cross purposes on this issue on account of a confusion of terminology.

MR. W. HARRISON (Siemens Electric Lamps and Supplies, Ltd., Preston): The non-additivity of brightnesses in heterochromatic measurements has not been widely appreciated hitherto, and Dr. Dresler's paper is particularly valuable in showing clearly the errors which can occur in equality of brightness matching with a colour difference present.

With reference to practical methods of visual heterochromatic photometry it would

appear that the use of a suitable visual colorimeter (for example, as mentioned on p. 337 of the revised edition of Walsh's "Photometry") is a good alternative to the flicker photometer method. The requirements of a colorimeter for this purpose are (i) adequate sensitivity to small brightness differences; (ii) sufficient choice of matching stimuli to enable a good energy match to be obtained, and (iii) means for reading accurately the luminances of the matching stimuli.

A point which may be of particular interest in understanding the non-additivity of brightnesses is whether the B/L ratio is a function only of chromaticity and is independent of the spectral composition of the stimulus. Would a yellow produced by a mixture of red and green have the same B/L ratio as a true yellow of identical chromaticity? From the paper it appears that it would, and that the B/L ratio is a function only of the chromaticity. Dr. Dresler's confirmation on this point would be appreciated.

DR. S. T. HENDERSON (Thorn Electrical Industries, Ltd., London): One of the most interesting points brought out by Dr. Dresler's treatment of the data is the lack of correlation between B/L and σ in the yellow region. This may have some bearing on the concept of saturation, which is normally used to indicate the subjective aspect of excitation purity σ. The latter, however, is defined in terms of chromaticities, without regard to spectral distribution, and it may be that the correlation of B/L should be with saturation considered as an expression of width of spectral distribution, rather than of mere "colour appearance." It would be interesting to do experiments on this, using yellow lights adjusted to the same chromaticity but of different spectral distributions—for example, sodium light, a combination of red and green lines, a combination of separate red and green bands or a continuous band from green to red. Differences in B/L would perhaps be revealed. Experiments on adaptation have indeed been done on similar lines by Cohen, who found no differences between yellow and "pseudo-yellow," but he did not use line spectra.

DR. DEANE B. JUDD (National Bureau of Standards, Washington, U.S.A.): Dr. Dresler has stated clearly the philosophy behind the internationally accepted C.I.E. definition of luminance and has placed the responsibility for conformity to this definition where it belongs, that is, squarely on the photometrist. His analysis of the experimental results demonstrating the non-additivity of heterochromatic brightnesses is helpful because it shows a new way to regard these results. This new view is based either on the assumption (Dresler) that flicker photometry under conditions yielding additivity actually evaluates brightness, that is, actually corresponds to a linear measure of the subjective appreciation of luminance, or alternatively on the assumption (MacAdam) that, when a subject reports two chromatically different fields to be equally bright, they really are. The similarity of the results of these two assumptions (Fig. 3 compared with Figs. 7, 8, and 9) goes far to support the first—otherwise rather shaky—alternative, for who is to know whether two fields are subjectively equally bright if the subject does not?

It may be worth while to recall explicitly an older view of the phenomenon aptly called by Dr. Dresler non-additivity of heterochromatic brightnesses. This view says that when a subject judges a highly saturated colour to be as bright as a more grey colour, he has a tendency to over-rate the more saturated colour; that is, he mistakes some of the saturation for brightness. The large individual differences are taken to mean that one subject makes a large mistake of this kind; others, a smaller mistake, or none at all. A disadvantage of this view is that it denies the possibility that a subject can make a valid judgment of brightness; he must be assumed to over-rate the more saturated colour more or less depending on the amount of his training. The correlation pointed out by Dr. Dresler between B/L and excitation purity could be

used, however, to support this view, and if he had used instead of excitation purity a better correlate of saturation, such as *metric purity*,* the support would have been even more striking.

The actual basis on which an observer adjusts the relative luminances of two fields of different chromaticity when he is instructed to make them appear equally bright, is unknown; and probably each observer does it somewhat differently. My own attempts to make heterochromatic photometric matches are based on the impression of nearness or solidity. If one half-field appears to me at the photometric dividing line to be nearer and more solid, so that I am looking past this half-field into the more filmy and softer colour filling the other half-field, then, to produce what I report as a brightness match, I raise the luminance of the softer field. Thus, for my own judgments, I doubt whether the brightness impression is primary. It is quite conceivable that saturation as well as brightness can contribute to the impression of solidity, and maybe some hues are more solid than others. Therefore I incline to the older view of these phenomena, but I recognise the admissibility and utility of the view developed by Drs. MacAdam and Dresler.

M. J. TERRIEN (Bureau International des Poids et Mesures, France): This paper shows admirably the advantages of the new term "luminance," with a precise and agreed meaning, leaving the term "brightness" available for less sharply defined notions, such as those handled here. It is to be hoped that the correct use of these terms will be extended generally with as much success as in France.

The meaning of brightness in this paper is quite clear, and is directly related to the sensation of light, colour and form being neglected. Would Dr. Dresler agree that the brightness of a given field is greater for a dark-adapted eye than for a light-adapted one? I would, without hesitation.

I think it worth stating that the views expressed by Tessier and Blottiau in the paper criticised by Dr. Dresler are not generally shared by the French photometrists, although they appreciate their experimental work.

The statement at the beginning of Section (3) that the "long-standing belief . . . traced to H. E. Ives's classic paper . . . has proved to be extremely misleading," was recently confirmed by extensive international comparisons of the transmission factor of coloured glasses by visual flicker photometry (Field 2 deg., illumination 25 lux, with surrounding illuminated field, against a light of colour temperature 2,700 deg. K). The transmission factors of two blue glasses (Schott BG 12 and BG 7) were found to be 10 per cent. too low compared with the factors obtained by physical photometry based on the agreed V_λ curve. Hence the flicker method undervalued saturated blue light matched against yellowish-white light. Red was correctly evaluated. This result is the mean of 96 widely spread individual results.

As regards the conclusion concerning a method of redetermination of a mean V_λ curve, Dr. Dresler's proposal seems to be sound, but the luminous sensations differ so widely with the peculiarities of the observer and the conditions of observation, that a revision of the now-agreed V_λ curve could bring endless discussions. Research is never to be discouraged, but an alteration of world-wide agreed conventions should not be contemplated, in my opinion, without very serious cause.

DR. W. S. STILES and MR. R. DONALDSON (National Physical Laboratory, Teddington): In considering Dr. Dresler's paper it is well to recall that the V_λ curve arose from the efforts of photometrists to compare the *value as light* of illuminants of

* Commission Internationale de l'Eclairage, Proceedings, 11th Session, Paris, 1948, p. 17; Proceedings, 12th Session, Vol. I, Stockholm, 1951, Technical Committee 7, p. 57.

different colour, their work being stimulated by the practical needs of the lighting industry. No system of evaluation other than a linear and additive one was seriously contemplated, and objections to any non-linear system for practical use are, we think, equally strong to-day. Ives—the pioneer worker in this field—abandoned visual acuity tests and brightness-matching in the presence of full colour difference as possible bases for a linear system of photometry because of anomalies of much the same kind as those Dr. Dresler has clearly summarised in his paper. Ives found that step-by-step brightness matching and flicker photometry gave similar V_λ curves, provided certain field conditions were observed, and the present C.I.E. V_λ curve was based on extensive American studies by these two methods, following Ives's work. (See J. Guild, Proc. of the Optical Convention, 1926, for an excellent account of the experimental basis of the C.I.E. V_λ curve). Ives also made some tests showing that flicker photometry was additive (this was about nine years before the work of Kohlrausch to which Dr. Dresler refers). The additivity of step-by-step heterochromatic photometry has not been tested to our knowledge, but even flicker photometry is not beyond suspicion. Apart from the breakdown in additivity under more extreme conditions to which Dr. Dresler refers, the results of a recent international intercomparison of the transmissions of coloured glasses by the flicker (and other) methods (see Terrien, J., Rev. d'Optique, 30, 45, 1951) are difficult to reconcile with the best determinations of V_λ by the flicker method.

Looking beyond the difficulties of photometric measurements as such, it seems certain that no linear system involving a single function V_λ will accurately define the relative luminous (as distinct from chromatic) values of spectral and non-spectral lights in all their diverse applications—in producing luminosity, serving as light signals, making possible various degrees of visual acuity, etc.—under the varying conditions of practice. Thus if a linear system is to be used the choice of a particular V_λ must be a compromise. The choice can be limited by an appeal to the principles of colorimetry, according to which two radiations of spectral distribution $E_\lambda d\lambda$ and $E'_\lambda d\lambda$ will appear identical in colour and luminosity if the three weighted sums $\int E_\lambda \bar{x} d\lambda$, $\int E_\lambda \bar{y} d\lambda$, $\int E_\lambda \bar{z} d\lambda$ have the same values in the two cases. Here $\bar{x}$, $\bar{y}$, $\bar{z}$ are the so-called distribution coefficients which can be determined directly from colour-matching experiments without any heterochromatic brightness-matching. It is true that $\bar{x}$, $\bar{y}$, $\bar{z}$, like V_λ, will also be dependent to some extent on the field conditions in the colour-matching experiments, but in the extensive range of intensities and colours for which Grassmann's laws of colour-matching are valid there is no additivity difficulty. If we have a satisfactory standard set of distribution coefficients $\bar{x}$, $\bar{y}$, $\bar{z}$, then clearly the standard V_λ function must be chosen to be a weighted sum of $\bar{x}$, $\bar{y}$, $\bar{z}$, $V_\lambda = A\bar{x} + B\bar{y} + C\bar{z}$ say. This is necessary if radiations which are colorimetrically identical are to be regarded as having the same photometric value. The condition is satisfied by the existing C.I.E. Standard V_λ, $\bar{x}$, $\bar{y}$, $\bar{z}$ functions, but the consistency was achieved by making the experimental colour-matching data—which did not completely determine $\bar{x}$, $\bar{y}$, $\bar{z}$—fit a previously agreed V_λ curve which had been obtained by heterochromatic photometry. Given $\bar{x}$, $\bar{y}$, $\bar{z}$, determined without appeal to heterochromatic brightness-matching there remain only two independent constants—the ratios A/B, B/C—at the disposal of the photometrist and into which

he must distill all the knowledge he has of the relative values *as light* of radiations of different colour (chromaticity).

It is fair to conclude from his paper that Dr. Dresler would choose these constants from measurements by the flicker method. This might have the advantage of facilitating visual photometry provided we were prepared to make much greater use of flicker photometry than at present. With the increasing use of physical methods of photometry, however, it is questionable whether much weight should be placed on this advantage. Another course would be to try to choose the two constants so as best to suit the assessment of luminosity differences when light stimuli are being compared which differ comparatively little in either brightness or colour. The way to do this has yet to be worked out in detail. Where large differences of colour are concerned, the fact that the relative luminances assigned by our photometric system might be considerably different from direct assessments of luminosity should not disturb us greatly because the assessment of luminosity under such conditions is not a very stable judgment, and, in any event, it is not clear that the values have much importance in lighting practice. Other procedures for fixing to the best advantage the two available constants may also be considered, but whatever choice is made the photometric system can only be a compromise, and anomalies of various kinds, including those described by Dr. Dresler, are inevitable.

Dr. Dresler is not, as we understand it, criticising the existing C.I.E. V_λ function —which, together with the present C.I.E. distribution coefficients $\bar{x}$, $\bar{y}$, $\bar{z}$, have proved generally satisfactory in practice—but he refers to a possible revision on the basis of new experimental work, and it is with the problem of how this should be done, if it proves necessary, that our remarks are mainly concerned.

DR. A. A KRUITHOF (N. V. Philips' Gloeilampenfabrieken, Eindhoven): Dr. Dresler's great merit is to have shown clearly that photometrists should be very cautious when comparing heterochromatic brightnesses with the object of assessing luminances. It was most impressive to me that even the "step by step" method is not safe.

The results dealing with equality of brightness matches have an unexpected parallelism with some phenomena in everyday life. Pigments showing saturated colours generally have a small total reflection factor, and consequently small relative luminance. Nobody, however, is aware that vivid red or blue colours are excessively dark. Previously I had ascribed this phenomenon to "practice," but Dr. Dresler's paper has made me think that physiological processess may have a great deal to do with it. It is a remarkable coincidence that both the B/L ratio and the enhanced brightness of saturated pigments are strongest in the blues and weakest in the yellows.

Non-linearity is the same as non-validity of the photometric sum-law. Now the colorimetric sum-law, which includes brightness matches, can be said to hold for all colours. I should therefore like to ask Dr. Dresler whether the colorimetric sum-law could hold exactly in spite of the failure of the photometric sum-law. Dr. Dresler states in his paper that "the brightness figure does depend on the colour of the other half of the photometric field." An interesting question is whether brightness can be considered a univalent function of chromaticity. The basic condition for this is that the same result is obtained by comparing two stimuli a and c directly and by comparing a and b and also b and c, the following relation holding good :

$$a/c = a/b : c/b.$$

It might be worth while to investigate this point.

MR. G. T. WINCH (Research Laboratories, General Electric Co., Ltd., Wembley): Dr. Dresler's paper is an interesting summary of published work indicating the extent to which, under certain conditions, heterochromatic "brightnesses" appear to be non-additive. The consequent implications with respect to the C.I.E. Standard Observer

data and its associated Photometric Scale may appear to be alarming. I feel, however, that he has tended to over-emphasise the importance of the large discrepancies recorded between the result obtained by flicker and equality-of-brightness photometers, as some of the data using a small field is not altogether consistent with results obtained by other workers, and much of the data relates to results obtained with large fields at low luminance. Bearing in mind that the C.I.E. Standard Observer and the Photometric Scale are based on photometry using a small field of approximately 2 deg. at a luminance of 25 equivalent metre candles or higher, the results quoted would have appeared in better perspective had Dr. Dresler taken into account all the published work.

For example, in 1934 Buckley (1) and Winch, Palmer, Machin and Dudding (2) published results of extensive programmes of heterochromatic photometric measurements on coloured filters and neon, sodium and high pressure mercury electric discharge lamps using a 2 deg. field Guild type flicker photometer, and also equality-of-brightness photometers, having both large and small fields. Most of these measurements were carried out at field luminances of 25 equivalent metre candles or higher. The measurements were made in photometric standardising laboratories by teams of 12 to 15 observers and our results were the mean of six observations on two or more occasions. The values quoted were derived from the point of intersection of the best line through the observed points and the unity Y/B ordinate, when the individual observers results were plotted against their Y/B ratios.

A few of the results which we obtained in 1934, showing the largest discrepancies between the flicker and equality-of-brightness photometer, have been abstracted and are contained in the following table. I have added a column (9) indicating the B/L ratios, for comparison with those quoted by Dr. Dresler. Similar results were obtained by Buckley(1).

All these results indicate that at the high field luminance levels associated with the C.I.E. Standard Observer data and the objective photometric scale, the discrepancies between the 2 deg. flicker and 2 deg. equality-of-brightness results, although appreciable, are considerably less than those indicated by Dr. Dresler, who has mostly quoted results obtained at lower luminance levels.

It was this situation, coupled with the laborious nature of the visual heterochromatic photometric methods, which led to physical methods being developed, which are steadily tending to supersede the visual techniques. Using modern photoelectric photometers(3), measurements can be made which are accurately in accordance with those which would be obtained by the hypothetical C.I.E. Standard Observer.

I feel that, provided the appropriate distinction is made between objective photometric measurements, made in terms of the C.I.E. Standard Observer, and the subjective visual comparisons made under other defined conditions of view, the apparent anomalies in Dr. Dresler's paper need not cause serious concern. Appropriate treatment of such results should be on the same lines as indicated for the colorimetric results obtained on the C.I.E. system and the associated subjective colour effects(4) due to different field size, luminance and simultaneous colour contrast and the conditioning of the observer before and during observation. In this manner the objective measurements in the C.I.E. system can be used to indicate the extent of the subjective effects.

DR. A. DRESLER (in reply): First of all, I should like to thank the Editor and the Papers Committee for having arranged this discussion, particularly since the various contributions show from how many different angles the problem of "luminance versus brightness" can be approached.

I agree with Dr. Walsh that if the full extent of the uncertainties of V_λ had

(1) Buckley. Illuminating Engineering (London), **27**, 118 and 148 (1934).
(2) Winch, Palmer, Machin and Dudding. G.E.C. Journal, **5**, 125 (1934).
(3) Winch. I.E.E. Journal, **96**, 452 (1949).
Winch. Instrument Practice, **5**, 137 (1951).
(4) Winch and Young. G.E.C. Journal, **19**, 203 (1952).

Data Extracted from Tables I and III of "Photometry of Coloured Light Sources"

Coefficient of Variation	Diff. of Unity Y/B	Largest Individual	B/L

Data Extracted from Tables I and III of "Photometry of Coloured Light Sources"

Filter Number	Method of Measurement	Field Illumination	Transmission	Coefficient of Variation of Observations from Y/B Line	Diff. of Unity Y/B Value from Spectral Transmission	Slope of Y/B Line	Largest Individual Difference from Y/B Line	B/L 2 deg. E of B Flicker
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
		Metre-candles	Per cent.		Per cent.		Per cent.	
Wratten 24 Red	Spectro Photometer (Photo-electric)	—	29.4	—	—	—	—	
	Flicker (Guild) 2 deg. Field	25	28.0	4.8	−4.6	+1.87	10.6	0.97
	Lummer Brodhun Contrast 6 deg. Field	25	25.6	11.1	−12.7	+2.50	18.8	
	Equality of Brightness 2 deg. Field	25	27.2	23.4	−7.2	+1.50	44.0	
Wratten 86 Yellow	Spectro Photometer (Photo-electric)	—	67.2	—	—	—	—	
	Flicker (Guild) 2 deg. Field	25	66.0	1.3	−1.8	+0.37	2.7	0.94
	Lummer Brodhun Contrast 6 deg. Field	25	64.4	2.6	−4.2	+0.19	4.0	
	Equality of Brightness 2 deg. Field	25	61.9	9.1	−7.9	+0.23	15.5	
Wratten 78A Blue	Spectro Photometer (Photo-electric)	—	29.6	—	—	—	—	
	Flicker (Guild) 2 deg. Field	25	29.5	1.3	−0.3	−0.14	2.9	1.09
	Lummer Brodhun Contrast 6 deg. Field	25	30.5	2.3	+3.0	−0.46	4.5	
	Equality of Brightness 2 deg. Field	25	32.2	12.9	+8.7	+0.17	29.0	

Type of Tube	Method of Measurement	Field Illumination	Intensity	Coefficient of Variation of Observations from Y/B Line	Diff. of Unity Y/B Value from Direct Result with Flicker Phot.	Slope of Y/B Line	[1] Largest Individual Difference from Y/B Line	B/L 2 deg. E of B Flicker
		Metre-Candles	Candles		Per cent.		Per cent.	
Osira Neon	Flicker (Guild) 2 deg. Field: Full Colour Difference	25	83.5	2.9	—	+1.10	5.5	0.93
	Lummer Brodhun Contrast 6 deg. Field: Full Colour Difference	25	74.5	11.3	−10.8	+2.20	27.3	
	Equality of Brightness 2 deg. Field: Full Colour Difference	25	78.0	22.2	−7.2	+1.70	52.5	
Osira Sodium	Flicker (Guild) 2 deg. Field: Full Colour Difference	130	5,150	1.9	[-]	+0.24	3.6	—
	Lummer Brodhun Contrast 6 deg. Field: Full Colour Difference	130	4,890	4.3	−5.0	+0.37	10.0	
Osira H.P. Mercury Street Lighting Type	Flicker (Guild) 2 deg. Field: Full Colour Difference	100	940	2.8	—	−0.95	4.8	1.03
	Lummer Brodhun Contrast 6 deg. Field: Full Colour Difference	100	980	3.0	+4.3	−0.56	5.7	
	Equality of Brightness 2 deg. Field: Full Colour Difference	100	970	5.9	+3.2	−0.40	9.5	

*By G. T. Winch, E. H. Palmer, C. F. Machin and B. P. Dudding.

been known in 1924, this function would not have been adopted by the C.I.E.—even provisionally. However, perhaps it was just as well, since nobody realised at that time that the adoption of such a function was a prerequisite for the successful introduction of physical photometry some 10 years later, as Dr. Walsh points out.

I doubt whether Professor Wright's views really differ as much from mine as he imagines. If *visual* heterochromatic photometry were really obsolete—as Professor Wright suggests—I quite agree that there would not be very much point to my paper. But the research workers from big, well-equipped laboratories are apt to forget that visual photometry is still frequently used in industry, particularly in the presence of *small* colour differences which the less-experienced observer imagines he can handle without difficulty. Moreover, the literature quoted in my paper shows that there *are* people who still believe that the eye can judge when heterochromatic luminances are equal.

Mr. W. Harrison is quite right in assuming that the trichromatic method is a "correct" one for visual heterochromatic photometry (see, for example, reference No. 7 in my paper). Unfortunately, it is a rather complicated affair. Regarding his second question (and Dr. S. T. Henderson's query on the subject) all experimental evidence so far available suggests that it is only the chromaticity and not the spectral composition of the stimuli that determines the B/L ratio.

I was particularly interested in Dr. Judd's reference to the concept of "metric purity." The correlation between B/L and metric purity is, in fact, more than striking. It means that the deviation from linearity in a heterochromatic equality-of-brightness match is a function of the difference in "apparent saturation" of the two colours matched. This immediately explains why the minimum value of B/L is in the yellow range, since this range has the lowest "metric purity."

I heartily agree with M. Terrien that the brightness of a given field is higher for a dark adapted eye than for a light adapted one. The results of the international comparison of various colour filters by flicker photometry are very interesting, particularly in the light of Dr. Stiles's remarks that these results are difficult to reconcile with the best determinations of V_λ by the flicker method.

Dr. Kruithof's reference to the unexpected parallelism between the B/L function and the appearance of saturated blue and red pigments in everyday life shows that we should indeed try to rid ourselves of the old idea that all spectral colours are of *equal* and very high saturation. The eye just doesn't work that way, and the varying distances between spectral colours and white on a U.C.S. chart give the clue to what we really should call "purity" or "saturation."

Dr. Kruithof's question "whether the colorimetric sum law holds in spite of the failure of the photometric sum law" has a straightforward answer. The problem is not one of heterochromaticity at all. It is the essence of a colorimetric match that, when it is accomplished, the two halves of the colorimeter field are indistinguishable, and, therefore, have the same chromaticity, the same brightness and the same luminance (see also the remarks of Dr. Stiles and Mr. Donaldson in their contribution to this discussion). In other words, there is no reason for a deviation from linearity, since the eye is not required to compare two heterochromatic surfaces. This explains, by the way, why the trichromatic method of visual heterochromatic photometry is a "correct" one, as suggested by Mr. W. Harrison.

Dr. Kruithof's last question refers to the problem already discussed above in my reply to Mr. Harrison and Dr. Henderson.

I am very grateful to Mr. Winch for having compiled the table based on the well-known 1934 papers. I don't think that I have over-emphasised the discrepancies recorded, since, to my way of thinking, the exact value of B/L is of secondary importance. What does matter is that B/L exists and that it exhibits a certain trend. Mr.

Winch's table clearly shows that his observers' B/L ratios for strong colours are smaller than those experienced by other observers. Whether this is due to the use of a special psychological technique by experienced observers when establishing an equality-of-brightness match (similar to that described by Dr. Judd in his contribution to the discussion), I do not know. I am, however, fully aware of the considerable irregularities shown by the observers I had at my disposal in 1936/37, few of whom could be regarded as thoroughly experienced. Some, who had shown a very large B/L on one day would not be able to reproduce it on another day and vice versa, while others showed greater consistency over a period. The B/L curves reproduced in Figs. 2 and 3 were actually based on the *average* results of *nine* observers, all of whom had to perform the required measurements on three different days. (For details see Table 5 of the original paper referred to as 6.)

Returning to my earlier comments on the importance of visual heterochromatic photometry to the practical man, I should like to refer to the results obtained when the equality-of-brightness match has to be made in the presence of relatively small colour differences like those between incandescent lamps differing in colour temperature by 300 to 400 deg. K. It has been established beyond doubt that the field brightness produced by the more saturated colour of the lamp of lower temperature is over-estimated by about 3 per cent. (i.e. B/L = 1.03). This was the main reason for the troublesome variations in the ratio of the Hefner Candle to the International Candle which was 1.11 at 2,080 deg. K (carbon filament lamp), 1.145 at 2,360 deg. K (tungsten vacuum lamp) and 1.17 at 2,700 deg. K (tungsten gas-filled lamp).

I quite agree with Dr. Stiles and Mr. Donaldson that the flicker photometer is by no means beyond suspicion with regard to additivity (see my remarks in Section 4 of the paper), and I also concur with their statement that we cannot expect a linear system involving a single function to define accurately the relative luminous values of spectral and non-spectral lights under the varying conditions of practical application. But I want to make clear that I have approached the whole problem as a photometrist, a photometrist moreover who has been slightly irritated by people who persist in the belief that the eye should behave in conformity with the mystic "hypothesis of the C.I.E." and who express surprise and even disbelief when they find that it does not—overlooking the fact that our "linear" photometric system is a matter of expediency and not a matter of visual judgment.

Office Lighting

Summary

The following is an account of a discussion on Post-War Building Studies No. 30, The Lighting of Office Buildings. Mr. P. V. Burnett, F.R.I.B.A. (Member), who was chairman of the committee responsible for the report, opened the discussion with the following brief summary of the report.

Introduction

A report has recently been published on the Lighting of Office Buildings. This is Post-War Building Study No. 30, and is of great interest to all those who have to do with the design and equipment of such buildings. It is the report of the Lighting Committee of the Building Research Board of the D.S.I.R.; the committee included in its membership a number of members of the I.E.S. and the R.I.B.A. Actually it is the second report of this committee, the first, dealing with housing and schools, having been published in 1944. Whilst the effect of this first report on housing has not been very noticeable, the effect on school design has been profound, and present regulations for the lighting of schools were strongly influenced by it. To this report can be traced the particular designs with which we are now becoming familiar.

The Report on Lighting of Office Buildings is the most comprehensive report on this subject that has been published in this country, because for one reason or another office buildings have been nobody's baby. Although there are large numbers of office workers, there have not been any regulations governing the lighting of offices. While there are the normal building by-laws, special or local acts like the London Building Acts, the Factory Acts and the Shops Acts, none include any specific standards of lighting for offices.

The study of the lighting requirements for offices had to begin from scratch, and a large volume of evidence was collected and considered before the report was completed; much of this evidence is quite new.

The development of office buildings in this country since the nineteenth century can be related to the growth of our foreign trade. In more recent years, the growth in the number of Government departments, and the increasing legislation that these departments administer, have also been important influences. The design of these buildings followed contemporary fashion and forms of construction for a long time, but eventually more attention was paid to functional needs including lighting, and there are a number of early examples of special designs for good lighting still existing. Good daylight became a planning requirement, but artificial lighting was regarded as being of secondary importance and does not appear to have had any influence on the design of the buildings.

In more recent times the development of forms of artificial light that merge easily with daylight has resulted in office blocks being planned which are deeper than could be lighted by daylight alone, and this tendency increased until some blocks of offices were considered (and perhaps erected) that relied on artificial light entirely, and had no daylight at all. This tendency has now evidently been reversed, and the pendulum has swung to the other extreme, because the most recent blocks of offices in America and elsewhere seem to be composed of vast windows covering the whole elevations.

In this country at present the evidence before the committee was that out of 1,408 office workers questioned, 37 per cent. complained of the standard of daylight in their offices, 7 per cent. worked in offices having no windows at all, and 41 per cent. complained about the standard of artificial light.

The report of the committee is divided into five main parts, plus appendices. The first part is a review of the development of office buildings in this country since Victorian

This discussion took place at a meeting of the Society held in London on March 10, 1953. Post-War Building Studies No. 30 is published by H.M.S.O.

times, and explains how the design of these buildings grew as a mixture of fashion, contemporary construction and early legislation. Buildings were designed individually, with scant consideration for their effect on the daylight of other buildings, and artificial light was regarded merely as an installation not really affecting the design. Only rarely were the functions of the buildings studied, the general aim being to crowd on the site as large an area as possible, irrespective of the conditions created for the office workers. Gradually, however, an improvement became apparent, and in the 1930s some notable advances in design were made.

The second part of the report deals with natural light only, and commences by pointing out that natural light is preferred in this country for office work, whatever may be the position elsewhere. Perhaps the greatest change referred to in this part of the report is the reorientation of modern thought, partly arising from the first report of this committee, by which the design of an office building is considered in relation to its effect on other buildings, in addition to its own interior lighting conditions; selfishness of individual developers must give way to " live and let live," and all buildings must be designed in the public interest according to modern town-planning thought. This change in ideas goes a long way towards improving the daylighting of office buildings, and makes the task of the designer much easier.

When considering a standard of natural light for offices, the committee found that the whole basis has to be quite different from that for artificial light. Daylight is not constant, in season, time of day, or even after it has penetrated through a window into an office; also, a compromise has to be reached between desirable intensity and distribution on the one hand, and what is possible in cities on the other. The committee heard much evidence on these different problems, and eventually recommended a standard of 1 per cent. sky factor at reference points 12 ft. from the outer face of the window wall. To reach this recommendation the committee had to consider the size of offices, the type of work, town-planning possibilities, window design and cleaning, the repeated desire of office workers for daylight, and the means by which such a standard could be applied by those unversed in the rather complicated technique. In addition, there was the important factor of merging light from fluorescent sources with natural light, a factor which affects the depths to which offices can be designed. With all these points to consider, the simple recommendation of the committee has much in its favour, but cannot be expected to avoid criticism. Incidentally, sunlight was not considered to be important for this purpose.

The third part of the report deals with artificial light, and follows the normal routine of considering details of office work, the value of illumination required, the brightness of the surroundings, light sources, the actual lighting units, the lighting of specific rooms, and installation details. Whilst this part contains little that will be new to members of the I.E.S., it is a valuable review, leading to conclusions which are broadly in agreement with the I.E.S. Code. Although the conclusions may not be new there are not yet many general offices in this country where the recommended standard of 20 lm./ft.^{2} is provided, and the large amount of evidence considered before that conclusion was reached should reinforce the views of the I.E.S. One of the main difficulties in providing satisfactory artificial lighting in offices is the wide diversity of the tasks, which may vary from reading blurred carbon copies on coloured paper to operating complicated accounting machinery, and the committee was greatly helped by an " Analysis of the Visual Task in Office Work " prepared by H. C. Weston, and which is printed in the report as Appendix IV. The sections on brightness of the surroundings, light sources, lighting units, maintenance, decorations, equipment, and furniture, all follow lines that will be well known to this Society, and the part relating to the lighting of specific rooms leads to conclusions closely in accord with the I.E.S. Code. It must be borne in mind that this report was prepared before 1950, because during the past two or three years there has been much development in the design of artificial lighting installations, particularly in America, reference to which was made

in the December, 1952, issue of "Light and Lighting." In this country, however, it can be said fairly—if with some regret—that we have not yet generally achieved the standards recommended in the D.S.I.R. report.

As, unfortunately, the enormous volume of work that still faces the building industry in this country makes it inevitable that many old and otherwise out-of-date office buildings must continue to be used for many years, a brief reference is made in Part IV of the report to possible improvements in the lighting of existing buildings, and the report winds up with a page of rather cautious references to legislative aspects. This latter subject is one where the committee, formed primarily of technicians, felt a little out of its depth, but, nevertheless, it was considered that some reference should be made to the need for regulations to ensure the provision of proper lighting for a type of work which is the daily lot of so many thousands of workers.

The appendices at the end of the report are of particular interest. The first consists of a Social Survey on Lighting in Offices; this was specially undertaken for the committee, and contains much information that will repay study by lighting engineers. About half the workers questioned had less than half the illumination recommended by the committee; about three-quarters worked under direct light from incandescent sources, and twice as many people complained of bad positions for their lights as complained about the amount of light. These are typical examples of unexpected information brought out by the survey.

The second appendix summarises some of the verbal evidence given by office staff associations, architects and surveyors, which, although brief, is valuable for the opinions of office designers and owners; the value of natural light is heavily stressed.

The third appendix is based upon a report of the N.P.L., and gives in diagram form the average natural illumination at Teddington over a period of 10 years at different times of the day for each month of the year. A chart is included, giving the times at which, on the average, certain selected values of illumination occur for any period of the year.

The fourth appendix has been referred to previously, and the fifth is a note on fluorescent lamps by R. O. Ackerley, most of which will not be new to this Society. Finally, the sixth appendix is a report on an actual example of what can be done to improve the lighting of existing offices.

I would not like to terminate my introduction of this report without mentioning that I stand before you as a very poor substitute for Sir Clifford Paterson, who was the chairman of the committee during most of its deliberations, and whose sad death all illuminating engineers mourn. The committee was also unfortunate to lose the valuable assistance of Mr. J. S. Dow, the late secretary of this Society, whose death prevented him from seeing the fulfilment of his work on this committee. In addition, between the publication of the first and second reports of this committee, there passed Mr. Percy J. Waldram, who, although not a member of the committee, was a welcome and pungent critic of the first report, and would dearly have loved to criticise the second.

Such men do not die in the ordinary sense; their work remains with us, enshrined in such reports as this, from which untold thousands may benefit.

MR. J. G. HOLMES: I read the report with considerable interest as soon as it was published last year, because many of us had been anxiously awaiting its publication ever since the material was collected in 1948. It does not contain much that is new, but the argument is so clearly stated and so well arranged that it becomes a valuable education to read through it. Mr. Burnett has summarised it admirably, and I will not attempt to go through it in any detail.

Most of us are office workers whose number is continually increasing, and so it seems to me rather strange that there has not grown out of all this trial and error,

any clearly accepted good practice of office lighting either for general offices or for mechanised clerical work. There is not much variety in the visual tasks associated with office work, but it is only in drawing offices and some private offices that there is any recognised practice for lighting. This report does not say much about what is best for office workers except to make reference to the treatment recommended in the I.E.S. Code, but it is difficult to apply those recommendations owing to the fact that the layout of desks, etc., in offices is generally related primarily to the natural lighting. The report recommends that the artificial lighting should be tailor-made to the requirements of the visual task, but then becomes inconsistent, saying that there should be good general lighting with local lighting when required. This is almost a fair summary of the recommendations for artificial lighting contained in the report.

I have the impression that the best office lighting is found in engineering and merchandising concerns where the management can see the results of good lighting either for factory work or for display. Offices concerned with clerical work only do not have this advantage of contact with good lighting, and although such offices are frequently badly lit, the workers in them may have no idea whatsoever about the relationship of their work to the lighting.

Running through the report is the implication that the provision of more light will give better lighting, and there is little warning that more light needs more care in design to control the discomfort glare and veiling glare often given by large or numerous lighting fittings. The report indicates that once the illumination level has been raised to the recommendations of the I.E.S. Code there will be little justification for further increase unless light becomes very much cheaper. I think this is entirely true. The report goes on to say that further efforts should then be directed towards enhancing the "quality of the lighting." There is, however, little guidance in the report to what constitutes "quality of lighting," and I hope that the discussion will produce something about the important aspects of quality in office lighting.

The recommendations in the report covering both daylight factor and artificial illumination level may be incorporated in some form of legislation, and this is probably desirable. Lighting in factories and schools has improved very considerably as a result of pressure by representatives of trade unions and Government departments, but home lighting, on which there was a comprehensive report in 1944, has not shown any marked change because there has been no organisation to enforce such a change. The illuminations levels recommended for offices are, however, relatively high, up to 50 lm./ft.^{2} maintained illumination, and at these levels it is not enough to state only what the illumination must be. At the lower levels required for factory lighting, considerations of direction, diffusion, glare, etc., are not so important as they are at high levels. If high illuminations are going to be mandatory it is essential that proper regard should be paid to problems of the direction and diffusion of light, and to the problems of contrast and glare. Careful consideration must be given to analysis of these problems before the report is given the force of law.

DR. H. H. BALLIN: As already pointed out by Mr. Burnett, this document contains a lot which is known to us as lighting engineers and it is rather difficult to find any particular point which can be taken up for criticism or further deliberation. There are, however, many good ideas hidden in the document which I am rather afraid may not be appreciated by the people who would really benefit from them.

After reading the document the first time I left it for some time and then came back to it with the idea that the authors had forgotten some important point, only to find it hidden away in an obscure paragraph.

Obviously if we try to base any legislation on this document there will be very little which can be taken from it as it is, but it would have to be elaborated, particularly where artificial lighting is concerned.

In view of the present situation where it is so often necessary to improve the

lighting in old buildings, perhaps more emphasis could have been placed on what can be done in this field. I think there is a close inter-relation of lighting with other aspects of physical environment. Quite often when people complain about lighting it is something else which is at fault. There was an example in the early days of the war when complaints were made that the temperature in some underground factories was too low. These factories were lighted with " blue " fluorescent lamps, and it turned out that it was because the lamps made the workers *look* cold and sick that they *felt* cold and sick. A lamp with a warmer colour was developed and overcame this psychological effect.

Another very important field is that of decoration and the treatment of furniture. Again this is covered in the report but it is doubtful whether the problem is sufficiently stressed to stop manufacturers of office equipment making everything a drab green, or to stop the manufacture of typewriters with shiny keys.

The suggestion of using supplementary lighting is interesting, but " white " fluorescent light may not always supplement daylight properly. We had an installation where half the office was lit with natural daylight and the other half had fluorescent lighting with warm white tubes. When we changed to " daylight " tubes the girls did not like it at first because they felt they did not look as nice as before. However, we persuaded them to keep the new lighting for a week and after that, with the better match of the lamp, they lost the consciousness of being in artificial lighting. Where supplementary lighting is required the " daylight " tube is best.

I am glad that in the discussion on lighting units the use of opal glass spheres is criticised, but a similar criticism of installations of industrial trough fittings or bare tubes in offices is not, in my opinion, sufficiently emphasised. I think the crime of employing bulky industrial trough fittings in well designed offices is one of the main reasons for the opposition which still exists against fluorescent lighting in this country.

It is interesting to note that the document comes down against indirect lighting People have been thinking that indirect lighting is the answer to office lighting problems but, apart from the fact that the brightness is in the wrong place and the light on the working plane is unsatisfactory, there is a general dullness with an installation of this kind which must be watched.

Another point is that of maintenance. This is indeed a serious subject for lighting manufacturers, because research departments are trying to increase the efficiency of light sources by an additional 1 or 1½ per cent., only to find perhaps that 50 per cent. is wasted by poor maintenance. Some people would like it laid down that the minimum illumination in an installation should not fall below a certain figure. This is dangerous if it becomes the basis of a general specification, but it is quite true to say that from the point of view of the maintenance engineer concerned such a responsibility would be most welcome. If it was laid down in some way that whoever was responsible for lighting installations must see that the illumination does not fall below a certain level, he would have to ensure cleaning of fittings, decoration of walls and regular replacement of lamps.

I think perhaps we are too keen on the idea of an average illumination throughout life. Nobody can catch anybody else out with an average illumination, but if you want a yardstick to discover whether an installation is giving satisfaction, I think something better could be found. I am aware of the difficulty of any specification laying down minima, but it is the maintenance question which is so important—perhaps something could be done. The trouble is, of course, that in an actual installation only a very small part is under the lighting engineer's control. We were asked by one client to specify the minimum illumination we could guarantee, and we eventually worked out that this minimum would be only something like 35 per cent. of the initial value—and of this drop of 65 per cent. only 25 per cent. would be due to the fall in light output

of the lamp, the remainder being accounted for by the fall in reflectivity of fittings, walls and ceiling through dirt and age.

I see here a challange and an opportunity for the Illuminating Engineering Society to give guidance and help to all who use artificial lighting. To maintain the required amount and quality of lighting is not only a responsibility of the manufacturer but is even more a responsibility of the user.

DR. W. J. WELLWOOD FERGUSON (President): Mr. Holmes has referred to the absence of an accepted practice of good office lighting. The answer is probably that while the increased output or turnover due to good lighting in a shop or factory is easy to assess, the pecuniary result of good office lighting is not so obvious.

A comment has been made on the percentage of people who, in response to a questionnaire, make complaints about lighting. In my hospital thousands of new ophthalmic cases are dealt with every year; the percentage of patients who make spontaneous complaints about lighting is almost nil. I only mention this to illustrate the fact that questionnaires perhaps tend to make people exaggerate complaints when compiling their answers.

MR. A. H. YOUNG: We were hoping to have present here to-night Mr. G. A. Coombe, who is the chief surveyor of the Prudential Assurance Co., Ltd., to give us views on office lighting from the point of view of the property owner. Unfortunately he could not attend, but he has written a letter which I would like to read:—

"I would have suggested that the whole of the report of the Lighting Committee of the Building Research Board and D.S.I.R. is tarred with the usual brush of the town planner striving for ideals against economics.

"It is a fact that a stockbroker, or a member of Lloyd's, would sooner have a dungeon in the Stock Exchange or in Lloyd's than a beautiful, naturally well-lighted office a mile away, and whilst that is so, it is quite impossible, economically, to erect buildings in congested centres with adequate natural light in all parts of the building. This does not mean that I discount natural light, and the sky factor of 1 per cent. for a depth of 12 ft. is the minimum for which architects should strive.

"I notice that the report says that in America most recent blocks of offices seem to be composed of vast windows covering the whole elevations. That is true, but my experience is that this is only done when striving for this daylight factor. It is by no means an essential because numbers of modern buildings, if not all, have floor depths of 50 ft. or more, and sometimes depths of as much as 250 ft., the new Prudential Building in Chicago being an example. I would say that the general tendency in America is office space first, and daylight factor very much second—all of which leads me to the conclusion that it is for architects to do as much as they can with the daylight they have available, but not at the expense of very valuable areas of floor space, and for illuminating engineers together with ventilating engineers, to produce the best possible working conditions artificially."

For my own views, there is one recommendation of the committee which has not been mentioned to-night. That is in paragraph 92, dealing with wiring installations. It says "The installation should be designed from the beginning as a fixed arrangement, closely related to the building frame, and capable of giving uniform illumination over the whole of the floor space." If this is not done, tenants' extensions from the few ceiling-lighting points that are provided are usually carried out in a variety of ways, many of which, besides being unsightly, bear little relation to the recommendations of the I.E.E. regulations. Whilst in many of the older buildings this is a difficult problem which is bound to arise, our experience has been that modern office blocks built since the war do follow this recommendation. They do have a general installation

throughout the office space, which enables a good uniform overall illumination to be achieved.

MR. W. ALLEN: Mr. Coombe mentioned the development of property in relation to daylighting. I do not know whether the report has failed in some point to make clear what I think Mr. Coombe has missed, namely, that the general proposals which the committee made, and which form part of the modern concept of town development, are the only way known at the present time of resolving the conflict between high density and reasonable amenity. It is an economic proposition, for the densities of development practicable within the committee's proposals are as high or higher than those which can be permitted for other reasons of town planning. The L.C.C. generally permits densities up to plot ratios of 6.5; in one or two areas there are higher densities, but for town planning they are anxious not to have any higher densities over very large areas. The main point is that if you do, in fact, build upwards in this character then either you release a very valuable amount of ground space, or you can put the same ground space to better use. If you have height control and do not have a density control then, of course, you simply compress all the building space between two layers while if, on the other hand, you fix the density and do not fix the height, you will get the densities required together with the amenities of more light, quietness, easier traffic flow, and so on.

We do know, for instance, that in one very large part of the blitzed area of the City, the whole of the accommodation can be rebuilt to meet the standards of the committee without going above an average of eight stories. There is, however, one difficult economic aspect to note—a site of upwards of three-quarters of an acre is needed.

In America the trend is very much this way. I was there last summer and was able to see that very distinctive addition to New York, the Lever Building. There the architect and client between them developed a building which conforms almost precisely to the proposals made by this committee. It is true that the density and the development of the site is somewhat lower than is usual in New York, but the authorities do not like these plot ratios of 12 or more that they have had in the past—they are not very nice things to handle from the town planning point of view. The new Lever Building is one which is very much liked by the authorities and its plot ratio is about 6.5 The ground floor is rather open, the first floor covers the whole of the site area except for a well lighting a patio, and above this rises a tower of about 14 stories. This, of course, houses offices for the owner company, not for letting.

This building represents in many ways the trends in modern American office lighting. Windows are glazed with pale green glass and are fitted with louvre blinds; having thus cut down the natural light the artificial lighting is on all the time. Although this seems somewhat anomolous, it is, in fact, highly successful because they are able to work over the whole depth of the building and still produce a reality of satisfactory working conditions in the middle of the floor. The advantage is that people do not feel that the edge of the room is any better than the middle and there is, therefore, a high utilisation of the whole of the floor space. It is possible, too, to apply the practice which American offices like of having rows of desks down the middle of the floor, with the manager at the end of the row.

The artificial lighting in the Lever Building is incorporated in the sound-absorbing ceiling, is either filament or fluorescent, and is entirely direct. I noticed that generally the brightness in the field of view is controlled by ribbed glass, a very marked trend in American office lighting practice.

MR. A. G. PENNY: I was not able to follow all of Mr. Allen's remarks but I understood him to support the speaker who criticised that part of the report which opposes complete reliance on artificial lighting. I, too, think this a matter for criticism.

The reference in the report is as follows: "In America some buildings have been planned without regard to daylight, reliance being placed on artificial light as the main illumination. It is not known whether buildings so designed are satisfactory, but the very deep office spaces made practicable by this means would affect fundamentally the economy of office blocks. Because daylight is greatly valued in this country it is not thought this treatment would find acceptance for new buildings. . . ."

To say that an idea which would fundamentally reduce the cost of building is not worth consideration seems an astonishing statement from a committee whose terms of reference are, amongst others, to make recommendations for further research.

I would suggest that a most important matter for research is to find out if there is a form of artificial lighting which is satisfactory as an alternative to daylight. Mr. Allen said that in America they *have* found a form of artificial lighting that workers find to be satisfactory, but apparently this report does not think it worth while even finding out anything about practice in America. Perhaps this report is based too much on the idea that if a standard of lighting adequate for the visual task can be established, that is sufficient. I would suggest that this is only the beginning. Big office blocks could be much more cheaply built if the lighting could be designed to make the office worker completely satisfied with some alternative to daylight.

MR. W. ALLEN: It is always entertaining to listen to Mr. Penny even if he has to somewhat distort the facts for his purpose. He did not bother to complete the paragraph from which he quoted, which includes this statement: ". . . even in new buildings it can make acceptable for daytime use the areas which cannot be properly daylighted. The factors necessary for success are described in the report."

This seems to me to cover some of his points at least, and it does not alter the viewpoint of the committee that you do need daylight before you have generally acceptable conditions. There is something about having daylight and having a view outside which matters. Having got that, you can supplement daylight successfully. While Americans often do not place much reliance on daylighting, they do place a great deal of reliance on good fenestration generally, in order to provide this "something" which people seem to want—namely, a contact with the outdoors.

MR. A. G. PENNY: Mr. Allen also did not quote the whole paragraph. His estimates related to methods of improving existing buildings, whereas the point I wanted to make was that this committee decided that complete artificial light was not worth study for new buildings.

MR. R. O. ACKERLEY: Mr. Penny has implied that this particular recommendation was omitted without proper consideration, but if he goes a little further he will find that a great deal of evidence was taken and a very strong opinion expressed on page nine of the report that daylighting was very much desired both by building owners and building users in this country. If Mr. Penny is prepared to put buildings up at his expense he may force people in a few years to do without daylighting, but in this country the committee found that people do not want buildings without daylight.

MR. F. C. SMITH: It became evident from the survey of office lighting that the general standard left much to be desired, and I think it would be right to say that the committee were conscious that the matter must be approached in the spirit of missionary enterprise if improvements were to be obtained.

I feel that this meeting in considering the report would go astray if it overemphasised any one feature. In my view there were at least three considerations that the committee had to take into account if its work was to be effective.

Foremost, it was necessary to consider humanitarian aspects. People who work in offices are not a lot of individuals without ideas, herded together to turn out work

and to keep records. Office workers are people with personalities, having individual likes and dislikes, and the conditions under which they work from day to day have a great deal to do with whether or not they are happy in their daily work. These considerations were, I believe, very largely responsible for the demand that offices should have, wherever possible, adequate daylight and a view from the office window.

Secondly, there is the serious problem of economics. It is not always recognised by people who advocate extravagant levels of illumination that the running costs for any given illuminant are almost *pro rata* to the illumination provided. If one wishes to get the co-operation of industry, it is therefore necessary to prescribe adequate, but not extravagant, levels. The committee tried to prescribe an adequate standard of lighting capable of economic achievement. The committee were fortunate in having available the fundamental work of Weston, which enabled the committee to prescribe illumination values having a sound technical and scientific basis.

Thirdly, there are the various technical aspects other than levels of illumination, and it is hoped that the general recommendations made in the report for promoting comfortable and easy seeing, as well as general well being, will be helpful and effective.

MR. A. CUNNINGTON: I want to confine my remarks to artificial lighting. I was interested to see that, rather naturally, the values of illumination recommended were closely modelled on the I.E.S. Code, and I could not help thinking, when looking at these figures, what startling advances have been made in the last 40 years. In 1912 I was engaged in measuring office illumination with the new illumination photometers, and I can vouch for the fact that the levels at that time were amazingly low. Even in the headquarters offices of this Society the illumination was only about 2 ft.c. I know it is almost impossible for us to realise that people did work in these low levels of illumination, but I often measured 1 and 1½ ft.c. where clerks were actually working. We must, of course, remember that in those days our homes and streets all had levels of illumination very different from those of to-day.

Turning to Part 3 of the report, there is a very important section dealing with brightness which I think is common knowledge to lighting engineers, but which I feel ought to be got over somehow to the people who have to do with artificial lighting. I am not thinking so much of large new blocks of offices which will probably be taken care of fairly well, but of the smaller premises where the local builder calls in a wireman to do the lighting. It should not be just a question of putting in a lighting fitting, but a matter of impressing on the lighting contractor the importance of other features, such as brightness and decorations. Unless these features are appreciated by such people it seems to me that this report will not have fulfilled the whole of its work.

While the survey is very useful for the statistical information it contains, from the illumination point of view I think a good deal of the value was lost by holding most interviews in the *afternoon* when, except during the middle of winter, artificial lighting is not normally in use. I have never been very favourably impressed with the idea of consulting the people using the lighting. For example, if the person in charge of a typing "pool" insists on consulting individuals, some will want one thing and others something quite different, and no decision can be made.

The report deals with the lighting of offices for typing, but it seems a little inconsistent to state that the best way to deal with such premises is to have a good general illumination with supplementary lights on individual desks. If you look at Plate 8 in the report, the typing pool shown there has been greatly improved by a new system of lighting in which all the individual lamps on the typewriters have been removed and replaced by a higher level of general illumination. I am fairly certain that the employees were not consulted when the change was made.

We have still a long way to go before the recommended values for office lighting

are adopted everywhere; I think, however, that it is an indication of a trend in the right direction when the investigators found that 8 lm./ft.^{2} on desks was common.

MR. J. G. HOLMES: According to the figures in Table 35 of the report, 3 or 4 per cent. of office workers have artificial illumination of less than 2 lm./ft.^{2}. The figure of 8 lm./ft.^{2}, which is given as representative in the report, usually relates to daylight plus artificial light.

MR. W. IMRIE-SMITH: In planning the lighting of offices other factors, such as ventilation, etc., have to be borne in mind, though it is not always easy to achieve the ideal in practice.

I handle a large number of architect's plans and find that very seldom is this fact appreciated when dealing with private offices. For example, when dealing with a small, square office leading from a passage, where should the architect put the door? In nine cases out of ten you will find it near the left-hand wall, which means that the occupant of that room, if he positions his desk to have the window on his left side, will be sitting directly in the draught between the door and the window. If the architect would only realise that with offices like this he should put his door on the right, you would then give the occupant a chance to use the available daylight correctly.

I think attention to this point would be a constructive step.

MR. P. V. BURNETT: Mr. Holmes was concerned with quality of lighting, and complained because we did not say enough about it in the report, and then he said that he does not know what it is. I agree, but we do not know either.

Dr. Ballin really gave a brilliant talk on the difficulties of fluorescent lighting, and if we had known about them in 1946 the report might have been different.

Our president referred to the fact that the users of offices are rather dumb and do not know what they want. I think that is a fair point and is true. If you go into industries where there are more jobs than workers you will find comments on lighting and everything else, but if you go into an office where there are more workers than jobs, you will find a certain caution. In the same way patients going into a hospital are also rather cautious.

Mr. Coombe's criticism of the report is the old story of town planners striving for ideals. I do not regard that as a criticism; quite frankly, if town planners are not going to aim for ideals what are the uses of town planners? I agree it is town planners striving against economics to some extent, but, nevertheless, I think it is a very good thing that this is so.

Mr. Penny did not like us saying that people in this country prefer daylight. We did not just imagine that idea. First, we had the Staff Association saying that the majority of their members wanted adequate daylight and did not consider artificial light was a proper substitute. We had evidence from architects and designers of buildings who said the same thing; evidence from surveyors who act for owners, who said that buildings with good daylight were worth more money. The Director of Lands and Accommodation, who deals with space for Government offices, said the same thing, so it is fair to say that we had much evidence. There is the social survey also, and in my introduction I was careful to stress the point that the preference for daylight referred to this country; I was not trying to make a comparison with America —it is in this country that this preference exists. As regards recommending research into buildings with no daylight at all, I do not think that such a recommendation was really a function of the committee.

Mr. Cunnington referred to small office premises, and I agree with him that it is difficult to inform people who deal with small office premises about quality of light. They are inclined simply to put a light in the middle of the room, but I think it is

possible, for example, to work on people like that. If the Government would give more publicity to these reports it is quite possible that there would be an improvement in that respect. I agree entirely about the difficulties of consulting users, but we have to ask them questions, and office hours are limited, so that questions were necessarily asked in the day-time.

Comparison with practice in the United States does not only apply to office buildings or lighting. In this country we appear to assume that because we speak a common language with the United States we think on the same lines. The fact is, however, that the conditions and people are so different that it does not follow that practice in America would be suitable here or *vice versa*.

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